



**VEHICLE MINIMIZATION FOR THE MULTIMODAL PICKUP AND  
DELIVERY PROBLEM WITH TIME WINDOWS**

THESIS

Benjamin Clapp

AFIT-ENS-13-M-03

**DEPARTMENT OF THE AIR FORCE**

**AIR UNIVERSITY**

**AIR FORCE INSTITUTE OF TECHNOLOGY**

**Wright-Patterson Air Force Base, Ohio**

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THESIS

Presented to the Faculty  
Department of Operational Sciences  
Graduate School of Engineering and Management  
Air Force Institute of Technology  
Air University  
Air Education and Training Command  
In Partial Fulfillment of the Requirements for the  
Degree of Master of Science in Operations Research

Benjamin A. Clapp, BS

March 2013

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Benjamin Clapp

Approved:

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Jeffery Weir, PhD (Advisor)

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Date

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Raymond Hill, PhD (Reader)

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Date

## **Abstract**

This thesis develops an algorithm to address a special case of the Vehicle Routing Problem. The algorithm developed is decompositional with two components. The first component is based upon Dijkstra's algorithm and is used to simplify the routing component of processing. The second component is based upon the priority rule heuristics used in scheduling job shop problems for parallel machines.

The VRP solved is subject to time windows and capacity constraints on vehicles and offloading. The VRP is multimodal. The objective function for the problem is the sum of all vehicles used, multiplied by their respective cost modifiers. Shipments are required to travel entirely on a single mode.

The data input consists of a network and shipping requirements. The network is subjected to Dijkstra's. Dijkstra's returns a simplified network of shortest paths. This simplified network, along with the shipping requirements, is subjected to the scheduling heuristic. The heuristic assigns as many of the shipments as possible away from the currently minimizing mode. This determines which shipments must be processed on the minimizing mode. It determines how many vehicles are required to carry those shipments. Finally, any remaining capacity is assigned. This process is repeated for each mode.

## **Acknowledgements**

I would like to thank Dr. Weir for guidance throughout the development of this thesis and especially for his aid in paring away what was unimportant and retaining what was essential in the problem. I would also like to thank my sponsor, David Longhorn, for providing the problem and for his insight into it.

I would also like to thank my family and my wife, whose support helped me through this process. Finally, I would like to thank the Air Force Institute of Technology and Transportation Command, for making this research possible.

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# VEHICLE MINIMIZATION FOR THE MULTIMODAL PICKUP AND DELIVERY PROBLEM WITH TIME WINDOWS

## I. Introduction

### The General Problem

The algorithm developed here addresses a special case of the VRP. The VRP considered is multimodal with time constraints. It is also subject to capacity constraints, both on individual vehicles and on offloading at each node. This makes the problem broadly equivalent to the general formulation of the M++RP, or multimodal multicapacitated vehicle routing problem. However, the objective function used is based upon the total numbers of vehicles of each type used. Consequently, the problem can also be considered to be a special case of the Fleet Size and Mix Problem.

The primary issue in solving any VRP is computational complexity. This is even more true when addressing the M++RP, or the FSMP. The computational complexity is exacerbated by the size of the problem and by the number of options available. It is not reduced by the constraints. In fact, the constraints may increase the computational

complexity of the problem. The constraints may cause this issue by creating interference between the shipments in their processing at specific locations or on specific vehicles.

The FSMP has three specific issues related to computational complexity, which substantially expand the problem. Firstly, the FSMP does not directly allow for tradeoff-costing, either between particular days or between vehicle types. We concern ourselves with the total number of vehicles used and not with the vehicles used on any particular day. Because of this, vehicles can be considered ‘free’ with respect to the objective function except if their assignment would cause more vehicles to be required. It is not always possible to infer directly how the assignment of one vehicle might affect the assignment of later vehicles. Because of this, the costs of assigning vehicles are generally unavailable, directly, until the latter parts of the assignment.

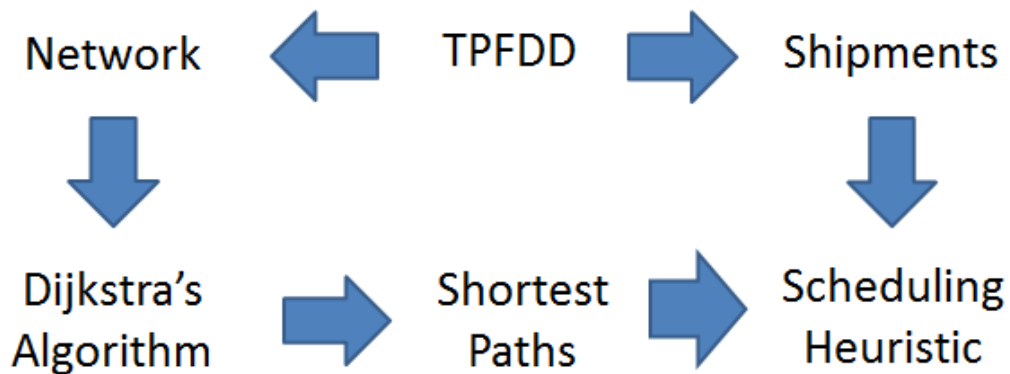
Secondly, in the FSMP, we do not know the number of vehicles available for any given mode. This makes capacitating flow on any given mode difficult. It also makes it difficult to determine the limitations on the number of shipments any given mode is capable of carrying. Without knowing what a certain mode can carry, it is difficult to determine what the other modes must carry.

Thirdly, the FSMP generally requires multiple iterations to solve. We are seeking the feasible solution using the fewest vehicles. The intuitive approach to this solution is to determine a number of vehicles which is obviously sufficient. We could then reduce the number of vehicles, checking to ensure feasibility with each reduction. This is functional because it allows the determination of each mode’s capacity interactively with the other modes. All methods of solution must somehow take this process into account.

Generally, this means correcting an original solution, which of course requires many solutions of the VRP for a single FSMP solution.

### **Algorithm Overview**

The algorithm developed in this thesis is decompositional. It handles the TPFDD by splitting it into two data-components. The first data component is the network, which is processed by Dijkstra's algorithm. Dijkstra's returns a simplified version of this network. The second data component is the shipping requirements. The shipping requirements and network are then used as input for the second part of the algorithm. This part of the algorithm is the iterative scheduling heuristic. It efficiently allocates the shipments included in the shipping requirements to vehicles associated with paths on the simplified network. This assignment is made so as not to violate any of the constraints associated with the network, vehicles, or shipments.



**Figure 1. Overview of Algorithm**

Dijkstra's algorithm is well-researched, very fast, and very reliable. In this instance it has only a small, conventional role. It seeks out the shortest path from each node included in the original network to each other node included in the original network. If we assume that the shortest paths are the best paths to use, we may use these paths in place of a full routing algorithm. While the paths are unlikely to be ideal, they approximate the ideal.

The second component of the algorithm is the iterative scheduling heuristic mentioned above. It iterates once for each mode. First, it determines the cheapest mode which is capable of carrying each shipment. At this stage, the algorithm assumes that the shipment is immediately loaded onto the mode on arrival, and when delivered, unloading capacity is immediately available. After this stage, the algorithm determines whether the number of shipments assigned to each mode is too great to be handled by the unloading capacity of that mode. Any excess shipments are moved to a higher-cost mode.

Finally, the number of vehicles required to carry any shipments assigned to the most expensive mode is determined. Then, any excess capacity is used to deliver shipments which were previously assigned to a cheaper mode. Any shipments which are assigned to the most expensive mode are eliminated from the overall shipment list. The process then repeats, disincluding the newly minimized mode. In the next iteration, the reduced shipment list is used.

### **Scope of Research**

The purpose of this research is to develop an algorithm capable of solving a large instance of the multi-modal FSMP. The algorithm will emphasize deadlines and arrival

dates as priority constraints in its solution. It will minimize vehicles in order of cost, ensuring that the most expensive vehicles receive priority. Each shipment will be shipped entirely on a single mode. Real-world aspects of the problem which are included in this solution include vehicle and offloading capacity and variation in path lengths.

### **Issues, Needs, and Limitations**

The research is limited by its inability to model the real world with precision. Many constraints are applicable to the real-world problem but beyond the scope of the algorithm. This is generally due to added computational complexity. As a consequence, the results given by the algorithm can only provide a guide to the number of vehicles ultimately required for any given TPFDD and network.

A major limitation of the system as it stands is the removal of constraints regarding which modes can carry certain shipments. Certain shipments, according to a TPFDD, are locked into a particular transportation type. This algorithm does not allow for such limitations, but instead assumes that all shipments can, at least theoretically, be carried by any mode.

Another major limitation is the lack of multimodal solutions that is apparent in the algorithm. Due to simplifying steps taken early in processing, the algorithm cannot address the possibility of efficient or effective multimodal solutions. However, it is likely that such solutions can be generated by slight modifications to the final solution set, as with a genetic algorithm or Tabu search.

## **II. Literature Review**

### **Chapter Overview**

The problem being reviewed in this text is a special case of the Dial-A-Ride problem, itself a special case of the Vehicle Routing Problem, the M++RP (Moccia et al, 2008) The Dial-A-Ride problem is a subset of the general pick-up and delivery problem, as defined in Savelsbergh and Sol's "The General Pick-up and Delivery Problem" (Savelsbergh et al, 2005) but the pickup and delivery problem is itself a refinement of the "Truck Dispatching Problem" originally proposed by Dantzig and Ramser in their eponymous paper. (Dantzig, 1959)

The Vehicle Routing Problem has received a great deal of attention over the years, but the particular refinement being dealt with in this paper is substantially less studied. In particular, the M++RP deals with multi-modal, multi-time constraints, and multiple capacity constraints, in addition to the constraints more usually associated with the VRP, but without depots. (Moccia, 2008: 2)

The problem can, however, also be approached as a special case of the sequential machine scheduling problem, for non-homogeneous machines, or the Q-machine scheduling problem. While the problem can be viewed as such, the more interesting applications of Q-machine techniques for this problem relate to the use of the Q-machine methods for solving the 'scheduling' component of a decomposed problem, and so that is where our study will focus.



This segment of the paper will first review the Vehicle Routing problem solution techniques, emphasizing the state of exact algorithmic solutions, and the decomposition and heuristic mixed methods for achieving large-scale near-optimal solutions, largely in order to clarify the difficulty of achieving a reasonably accurate solution in a short time-scale on a problem with such great computational complexity. Then we review the techniques used in Q-machine scheduling as approaches to the solution of the decomposed problem.

### **Vehicle Routing Problem Overview**

The vehicle routing problem is the problem consisting of finding an optimal route for either one or multiple vehicles between multiple locations, each of which will generally place a load on the vehicles, to be transported to a second location. This second location may be the depot of the truck, in simpler problems, but is often a delivery location. In this case, the problem becomes the Vehicle Pick-up and Delivery problem; more specifically, the problem may be constrained to require that the pick-ups and deliveries occur according to a certain schedule, in which case the problem becomes the Vehicle Pick-up and Delivery Problem with Time Windows.

### **Dial-A-Ride Problem Summary**

The most studied problem class which closely resembles the one discussed in this paper is known generally as the ‘Dial-A-Ride’ Problem. The Dial-A-Ride problem is a special case of the Vehicle Pick-Up and Delivery Problem with Time Windows, with vehicles operating from and returning to an established depot. The problem is subject to

vehicle capacity constraints and constraints on the maximum amount of time a customer may ride in the vehicle.

The Dial-A-Ride problem differs from the studied problem in several particulars. The first is that the Dial-A-Ride problem does not generally have to deal with infrastructure constraints on loading or offloading of shipments. This allows the problem to be simplified in significant ways, since a node cannot be occupied by a vehicle's unloading, and unusable to other vehicles, from other paths. The vehicles, however, may interfere with one another, if the capacity constraints on the arcs are used to create that effect. The second is that the Dial-A-Ride problem generally deals with homogeneous vehicles, rather than the multimodal approach required in dealing with the studied problem. This creates additional computational complexity, for two reasons. The first is that the various vehicles can be traded off, one against the other, providing another aspect of complexity, rather than simply requiring the addition of more homogeneous vehicles (as in the Dial-A-Ride problem) the second constraint is that the path from any given node to any other node is unique in the Dial-A-Ride problem, as generally understood, rather than having different distances and speeds for different modes. Finally, perhaps the biggest difference between the Dial-A-Ride problem and the problem studied here is the problem of scale. The Dial-A-Ride problem generally deals in vehicles which are each capable of handling multiple loads, whereas the problem studied here generally deals in loads which will require multiple vehicles. Hence, in the Dial-A-Ride problem, the core issue is ensuring that the vehicles waste as little travel time as possible in getting as many loads as possible to as many locations as possible. For the studied problem, the emphasis must be on ensuring that the correct vehicles travel to the correct locations at the correct

times, so as to prevent conflicts, and most importantly ship them efficiently and cheaply. Finally, the Dial-A-Ride problem is often solved for a single vehicle, rather than for multiple vehicles. While the Dial-A-Ride problem can be extended easily from a single-vehicle technique to a multi-vehicle solution under many circumstances, the particulars of the M++RP make it ineffective to extend from a single vehicle solution to multi-vehicles, especially since the particular problem being studied has as one of its primary objective function the use of minimum numbers of vehicles of each type.

### **Dial-A-Ride Problem Solution Techniques**

The Dial-A-Ride problem is computationally complex, but also very fragile. The number of variables involved means that the cost of accurate solutions to large-scale problems is often prohibitively high, and instead heuristic models must be used. Nonetheless, exact solutions can be found for the smaller problems, and have been. There has also been significant research into the extension of high-optimality techniques for problems after decomposition or alteration. However, the most interesting part of these techniques, for our purposes, is the development of decomposition and simplifying techniques to be used in conjunction with heuristics. For the Dial-A-Ride problem, it is often possible to simplify the problem to the point where an exact solution to the problem becomes feasible, even if the problem loses some fidelity in the process; for the M++RP problem, and more specifically, for the pragmatic instance of the M++RP problem being studied in this paper, simple decomposition will not result in an exactly solvable set of problems.

In 2004, Lu and Dessouky demonstrated a method for efficient generation of exact solutions to the Dial-A-Ride problem. The method was reliant upon an integer programming formulation of the problem, which was then solved using a simple branch and bound technique. It solved a problem consisting of 5 vehicles and 17 customers in under three hours. This demonstrates the complexity of the problem, since using only 5 vehicles and 17 customers generated that level of computational demand. The advantage of Lu and Dessouky's innovation was that it added a level of softness to calculations regarding time and capacity constraints; however, even with these significant changes to the fundamental paradigm, the algorithm produced a relatively time-costly solution to a relatively small problem. (Lu et al, 2004)

Psaraftis demonstrated an exact algorithm for the solution of the Dial-A-Ride problem in Transportation Science, dealing with multiple vehicles. His technique provides an exact solution, using a dynamic programming algorithm, which efficiently and effectively calculated the best method for dispatching the vehicles, including route and schedule. Originally, Psaraftis developed the technique for a fairly simple variant, involving only one vehicle, but it was eventually extended to fairly complicated multi-vehicle variants, including time constraints. The downside of Psaraftis' approach is that it only optimizes with respect to total distance travelled. While total distance travelled is of a certain commercial interest, it is effectively irrelevant to our particular problem because of the scaling issue. In our problem, distance travelled is a concern secondary to our primary goal- as we know, ultimately, that our vehicles must travel from pickup to delivery, and then to pickup, rather than the interchanging sequence possible in the generic Dial-A-Ride problem. Equally, Psaraftis' solution does not address the problem

of total vehicle number, which is what our algorithm is ultimately designed to address. (Psaraftis et al, 1980, 1983).

More useful to us in this instance is the generation of large-scale solutions to the Dial-A-Ride problem, which generally involves a heuristic approach. In most cases, the approach consists of a simplifying step, followed by an algorithm which approximates solutions to the reduced problem. In simpler cases, the problem is simply reduced directly using an analytical approach as in the generation of lower and upper bounds, and then solved exactly, or very closely. In large scale cases, the problem is decomposed and then approached with a heuristic technique, which provides a lower-quality but equally lower-cost solution to the problem, and is often the only feasible approach to such a problem.

Baldacci et al begin by generating a specialized integer formulation of the problem, and then the dual of that form. They then use two heuristics in conjunction to achieve a near-optimal resolution of the dual, which in turn they use to determine which paths meet certain lower-bound and upper-bound criteria. They then remove all paths which are outside these bounds, and solve the reduced problem using an integer programming technique, or if the problem remains too large, attempt to resolve the size disparity using branch-and-bound techniques. (Baldacci, 2011)

Sexton et al (Sexton, 1985) relied on Bender's decomposition, separating the problem into a 'routing' component and a 'scheduling' component, and then solving with a heuristic. This technique is very efficient for the resolution of the Dial-a-Ride problem, because the paths are effectively independent of scheduling. If one can determine which paths are most efficient, then the problem should nearly always solve optimally subject to those paths, which allows for a drastic reduction in the complexity of the problem.

While these decompositional techniques are effective in resolving some of the computational complexity of the problem, the decomposed problems remain very complex. Even after decomposition of the problem, we are left with a routing component equivalent to solving the shortest path problem for each of the customers, and a scheduling problem for parallel machines. While this technique is reasonable for resolving a problem involving only a few nodes, arcs, customers, and vehicles, handling the problem becomes substantially more difficult at larger scales.

An approach to multi-modality for a flexible number of vehicles was developed by Moccia et al, and focused upon the use of column generation heuristics. In this case, the formulation of the problem used ‘virtual networks’ to represent multimodal shipment transfers, developing false links with associated cost functions and time costs to represent the price of transferring from one mode to another at a given linkage. This methodology results in a reasonable solution for relatively large variants of the VRP. However, the algorithm used in the paper could only handle a relatively small system, though with great fidelity. (Moccia, 2008)

### **Dial-A-Ride Discussion Summary**

Solutions to the Dial-A-Ride problem are very rarely exact, depending instead on heuristic algorithms, often combined with decomposition, to solve even relatively simple problems. This is partly due to the limitations imposed by integer programming formulation, which the majority of the techniques use as a beginning for their solution. Any integer programming formulation must address tens of thousands, or even hundreds of thousands of variables, addressing which path, if any, each vehicle must be on at

which hour of which day, carrying what load. By extension, almost any solution to a large-scale Dial-A-Ride problem relies on a simplifying step, followed by powerful heuristics- and even so, will generally provide only a relatively slow solution to a relatively small problem.

For more details on the history of methodologies for studying the Vehicle Routing Problem, readers are recommended to *Fifty Years of Vehicle Routing* by Gilbert Laporte, in the 43rd issue of Transportation Science.

### **Q-Machine Scheduling Summary**

One approach to the M++RP problem is to reduce it to a scheduling component and a routing component. Once the shortest routes have been determined, the problem can then be handled as a scheduling problem, treating each of the modes for each path as a machine, with the vehicles treated as a global resource shared between the machines.

The transformation of the problem to a Q-machine scheduling problem reduces the complexity of scheduling significantly, but we are left with a highly computationally demanding problem nonetheless. At this stage, integer formulation of the resulting problem becomes more feasible and extensible to very small variants of the problem (Wagner, 1959) but the establishment of a more effective heuristic technique remains necessary for moderate to large scale scheduling problems. (Verma, 1999) In many cases, the most efficient method remains a scheduling ‘rule,’ modified as necessary by evolutionary algorithmic techniques to improve upon the initial high quality solution. Because of the issues of interference between various shipments, even a minor shift in the location of a single shipment can have major cascading effects on the efficacy of the

solution as a whole. This is particularly true as the chosen metric, number of vehicles used, is dependent upon peak usage across the various vehicles, not upon the total usage of each vehicle type.

## Q-Machine Scheduling Heuristics

The simplified form of the M++RP that we are solving in this instance is equivalent to solving  $Q_m | s_{ijk} | \sum w_j T_j$ , or the parallel machine scheduling problem with machines with non-equal speeds, which are not dependent on the specific job, with setup times, in order to minimize tardiness, and then modifying that schedule in order to minimize  $m$ , while holding the previous objective value static. This variant of the problem has seen significant research because of its industrial significance, and consequently, many algorithms have been developed and applied to the problem. However, extending an exact solution to large instances of the problem remains elusive.

Most solutions to the  $Q_m$  formulation for large problems rely upon a prioritization heuristic, but unfortunately no single index appropriately addresses  $\sum w_j T_j$ , and even if it did, the flexible nature of the number of machines means that while we could solve for weighted tardiness, we would not be able to prioritize reduction of machines; priority rules by definition assign a job to the first free machine, rather than attempting to reduce total machine numbers.

For  $\sum w_j T_j$  specifically, priority rules are difficult to implement because of the complex nature of allocation. No specific variable, ratio, or difference can provide an efficient and effective index in all instances. Instead, the ATCS prioritization rule was



developed, as a combination of all of the factors which might cause a particular job to be the priority job for a particular freed machine, weighted dependent on the particular characteristics of the machines and jobs.

The Apparent Tardiness Cost with Setups is one heuristic which has been developed to handle  $Q_m |s_{ijk}| \sum w_j T_j$ . The ATCS calculates an index based upon the processing time, setup time, objective weights, due date tightness and range factors, and the severity of the setup time. When a job is completed, the job with the next highest index is assigned. The Apparent Tardiness Cost with Setups is very efficient at handling large scale problems, and is equally very effective at generating an optimal or near-optimal solution. However, the ATCS does not effectively handle the in-parallel nature of the infrastructure constraints which are to be dealt with in the current problem, simply because those constraints are not factored into its system, and requires as part of its algorithmic structure the existence of a defined number of vehicles. Regardless, the ATCS is a very efficient approach to the large scale problems being handled in this instance for minimization of weighted tardiness. It is worth noting that in the seminal paper on the topic, Lee used a corrective simulated annealing technique to improve on the value of his final solution, relying on the ATCS rule only to generate a feasible high quality initial solution. (Lee et al, 1997)

Beyond the constructive algorithms, designed to generate a feasible and near-optimal solution, we find refining algorithms, designed to improve on an existing schedule. These techniques generally apply a local search heuristic, moving from one good solution to similar solutions stepwise. Two of the most commonly used heuristics in

this role are Simulated Annealing and Tabu Search, each of which searches locally to for improvements to the currently generated schedule.

Simulated Annealing techniques depend upon a large number of solutions, which randomly are traded for other ‘nearby’ solutions. Better solutions are generally preferred, and as the algorithm progresses, the preference for better solutions increases, until the algorithm is simply stepping to the local optimum. Similarly, Tabu search allows for an algorithm to pass into infeasible territory, if the objective function can be improved by doing so, by providing a penalty function associated with the infeasibility. As the algorithm progresses, it increases the penalty to achieve an effective hard feasibility.

### **Q-Machine Scheduling Summary**

The solutions to Q-Machine scheduling expose us to the idea of prioritization rules which allow for the solution of the problem for particular objective functions. These methods are not effective for solution subject to the specific criteria of vehicle minimization, but they provide a starting place for the development of our own rules and solution index.

Simulated annealing and the Tabu search show us the next potential stage of the development of the research, which is to develop a refining algorithm, along Tabu, simulated annealing, or evolutionary algorithm lines and use it to refine the solution into a specific high quality solution. The difficulty in implementing such a solution lies in the complexity of handling hundreds or thousands of large scale solutions to the problem. Without those, the refinement the heuristics can provide is minimal; with them, the algorithm becomes cumbersome.

## Pragmatic Instance Summary

In this paper, the particular problem we are studying is the M++RP problem, at large scales. The particular instance of the problem which is being discussed which we are using as a pragmatic instance of our general problem is a Troop Phased Force Deployment Data, or TPFDD. A TPFDD consists of a large number of transportation requirements, from a number of sources to a number of sinks, across a defined network. The development of transportation requirements and vehicle numbers required to move them is an interactive multi-stage process, as the number of vehicles themselves necessitate infrastructure and movement capacity at the vehicle level. According to Clausewitz' *Principles of War*, "The provisioning of troops, no matter how it is done, whether through storehouses or requisitions, always presents such difficulty that it must have a decisive influence on the choice of operations."

As a consequence, it is of particular importance to be able to quickly generate reasonable estimates as to the number of vehicles of various types required to execute a TPFDD, as generating these estimates will most likely be required multiple times, in a feedback process with both analysts and decision-makers. However, a TPFDD is remarkably large; as many as ten thousand transportation requirements (customers), across a network of as many as several hundred nodes, with multiple modalities, over the course of weeks or even months, subject to constraints on earliest and latest arrival, as well as to constraints on infrastructure for offloading that will be available, and potentially to many other over-riding constraints which are beyond the scope of this model.

It is a priority in all strategic situations to ensure that all deadlines and earliest arrival dates are met, subject to feasibility; the number of vehicles used is secondary to the accomplishment of the purpose behind the TPFDD, which may rely on any particular requirement or any subset of them being performed to requirements. For this reason, the algorithm generated here must prioritize first that all deadlines are met and only as a secondary concern handle the vehicle minimization techniques.

With that caveat, the solution of a vehicle minimization problem requires a complete solution for the problem including vehicle allocations and paths, because of the interaction of infrastructure capacity requirements. Because of this, and because any given solution will tend to depend on the number of vehicles available, the problem must be solved multiple times during any particular attempt to minimize the vehicle numbers. At the very least it must be solved once for each mode. This places an even higher priority upon high processing speed than was already necessitated by the size of the problem and the requirement for interactive feedback.

In the particular problem being studied it is noteworthy that the shipments will nearly always require multiple vehicles to carry; this allows for certain simplifications and changes of emphasis in the details of our algorithm. It is also worth noting that since the particular scope of the TPFDD is in-theater, in our application we are unlikely to find a solution that requires transshipment from one mode to another; instead, despite the multi-modal nature of the problem, we may with reasonable safety confine ourselves to the use of single modes for the duration of the trip, assuming the cost and availability of transshipment to be prohibitive.

## Chapter Review

Our final summary concludes that the particular computational complexity of the large scale M++RP requires an approach which is computationally simple, as in the Q-Machine scheduling priority rules, applied to a simplified problem generated according to the decompositional rules used for smaller Vehicle Routing Problems. With the combination of these two techniques, we can drastically reduce the calculation time required for the generation of a feasible solution, without sacrificing unduly the optimality of our solution. The interactivity of our pragmatic instance specifically encourages this, as the solutions are intended as springboards for analytical thought, rather than implementable final answers.

With this sort of rough-cut approach to a problem of this computational complexity, the emphasis must be placed upon reducing the processing time required to handle the problem. Without careful management of processing time, we run the risk of an impractical or impossible technique, which will fail to generate the timely, effective solutions required.

For this reason, our ultimate implementation relies upon a series of priority rules, applied in careful order to the shipments, and solved in a specific order in order to preserve feasibility, while minimizing vehicle number requirements.

### **III. Methodology**

#### **Broad Analysis of the Algorithm**

At the highest level, the algorithm consists of three major steps. First, the incoming data is separated into a network component and a shipping requirements component. Second, the network component is processed using Dijkstra's algorithm, to create a network of shortest paths. Finally, the scheduling heuristic assigns the shipping requirements to the simplified network at need. This organizational hierarchy will serve as the structure for this chapter, as we follow the flow of data processing throughout the algorithm.

#### **Data Inputs**

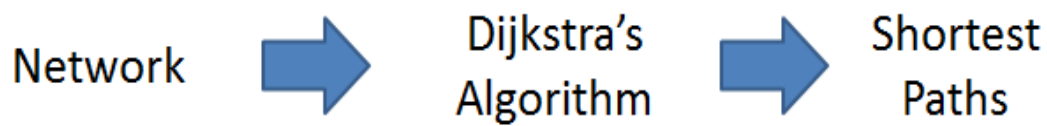
The algorithm requires three different major data components. The first of these components is the network itself. The network is composed of a series of nodes, with associated distances between them, and a value for the daily unloading capacity of the nodes in the units which are later used for shipment weight. Each of these distances and unloading capacities must be defined for each mode. In the case of a node-node pairing which cannot be travelled by a specific mode, it is possible to assign a 'big M' value for the transportation distance in order to force the shipment onto a higher-cost, but feasible, mode of transport. However, doing so can only cause the algorithm to transfer the shipments upward in cost.

The second component of data required is vehicle information. The algorithm requires data on vehicle speed, capacity, and the number of modes. This must parallel the number of parallel modal networks provided. These data are used throughout the algorithm. Speed, particularly, is used in all three major components of the scheduling heuristic, either directly or indirectly.

The third component of data is shipping requirements. Shipping requirements are stored as a series of lists. Instead of directly manipulating the data associated with the shipment, the algorithm uses the number of the shipment as a serial. Moving only integer values reduces the time required to sort and generate lists significantly.

### **Dijkstra's Algorithm**

Dijkstra's algorithm is used in place of a more complicated routing solver in order to approximate the ideal routes for vehicles. The shortest paths generated by Dijkstra's are good approximations if the vehicles are generally required to return to their depot after delivery to only one site. If this is held to be so, the routing problem becomes generally the problem of travelling from point A to point B to point A as efficiently as possible. This is equivalent to the shortest path problem.



**Figure 2. Dijkstra's Algorithm**

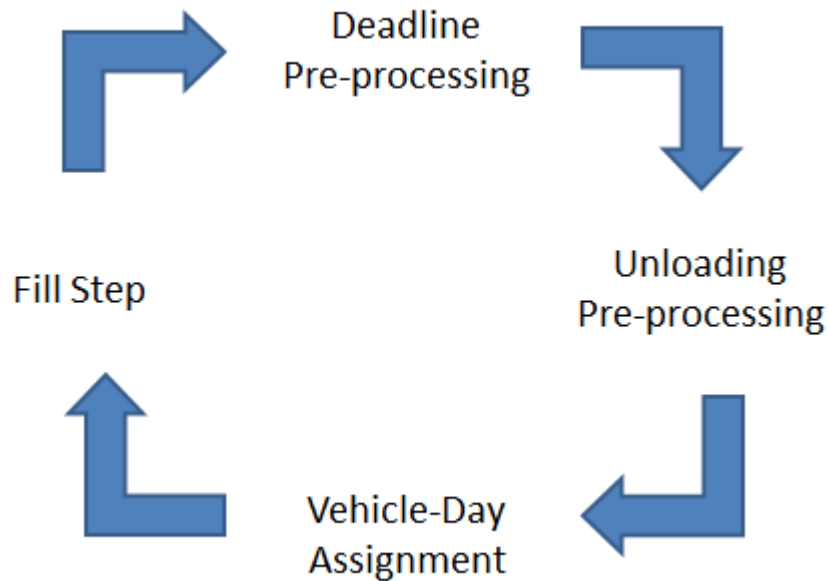
Dijkstra's algorithm is a very efficient algorithm for solving the shortest path problem, provided that the distance desired is from each node in a network to each other node in the same network. It works by expanding upon paths of known distances and tracking the shortest path discovered to each node. At each step, it advances to the next nearest node to the origin node. It records any nodes for which the shortest known path is longer than the distance to the current node from the origin node, plus the distance from the current node to the observed node. It then corrects their distances down to the newly discovered shortest path. Finally, it advances to the node which is the next closest to the origin node, after the currently selected node.

### **Scheduling Heuristic Overview**

The scheduling heuristic used in this algorithm is ultimately the core of the entire procedure. Dijkstra's algorithm can be viewed as a pre-processing stage that puts the input into a form conducive to the use of the scheduling heuristic. The scheduling heuristic bears special attention, especially as it comprises the majority of the complexity of the algorithm as well as the key part of its function.



The scheduling heuristic has four key parts; these are: Deadline Assignment, Infrastructure Assignment, Vehicle Assignment, and the Correction Step. Deadline Assignment and Infrastructure Assignment can be viewed as pre-processing steps, Vehicle Assignment as the core step, and the Correction Step as a post-processing method. However, each of these steps will be iterated once for each mode, as the overall heuristic determines the minimum number of vehicles required for only one mode at a time.



**Figure 3. Scheduling Heuristic Overview**

### **Scheduling Heuristic Inputs**

The inputs for the scheduling heuristic have two sources. The first is Dijkstra's algorithm, mentioned above, which provides us with a simplified network of shortest paths for use in the calculation of distances throughout the heuristic. The second is the

shipping requirements component of the original data, which is passed on in the form of a list of shipment numbers and a series of associated lists detailing arrival date, shipment size, and deadline, all accessible using the shipment number as a serial. The algorithm also acquires the vehicle data directly from the original listing.

### **Deadline Assignment**

Deadline analysis is the simplest of the four stages of the scheduling heuristic, and the quickest. In deadline analysis, each of the shipments has a time-available value calculated, which is simply the difference between arrival date for the shipment and the deadline date. This is the amount of time that a shipment is available for shipping. We compare this value to the speed of each mode and the distance for that mode between the source and sink for the shipment, then, add the amount of time required to unload the shipment. A mode for which distance/speed plus unload time is greater than the time available certainly cannot carry a given shipment. As a consequence, we know that the shipment must be moved higher in cost- to a faster mode.

Deadline analysis serves two functions simultaneously. First, it ensures that shipments which would be required to run on a more expensive mode for reasons of available time are assigned upwards earlier. This saves the time of calculating that they must be pushed up during the more computationally intensive infrastructure assignment stage. Second, it ensures that these shipments cannot cause other shipments to be forced upwards during the infrastructure stage.

When a shipment's cheapest potentially feasible mode has been determined by the deadline function, it is assigned to a list associated with that mode. There is a list for each

mode at the end of the deadline stage and each shipment will be in one, and only one, of those lists. These lists form the input for the Infrastructure Assignment stage of the algorithm.

### **Infrastructure Assignment**

Infrastructure Assignment can be viewed as another preprocessing stage of the algorithm. However, it is also fair to consider the Infrastructure Assignment stage as the stage of the algorithm wherein the unloading constraints are taken into consideration. While unloading is considered at the Vehicle Assignment stage as well, it is at this stage that it is most likely to cause a shipment to be moved or bumped from a mode, as opposed to simply forcing rescheduling. In other words, this is the stage where overall capacity of infrastructure unloading is taken into account.

This is achieved using a 2-dimensional array of doubles. Because we handle each mode separately, it is not necessary to maintain the full node-mode-day pairing for tracking unloading. Instead, we simply track the node-day pairing for the mode which is currently being analyzed.

The algorithm starts from the earliest arrival date, and begins to check through the list of shipments assigned to the particular mode. As it iterates through the shipments, if it finds any shipment with the arrival date it is currently searching for, it attempts to assign them immediately to the mode. If it fails, it adds them to the list for the next most expensive mode. If there is no more expensive mode, the shipment is retained at this mode. After processing through the list once, it increases the arrival date by one and

processes through again. This is repeated until all shipments have been processed through the system.

Processing based upon earliest arrival date is known as the EAD priority rule. This rule has several advantages. Primarily, it ensures that the infrastructure begins work as early as possible. That is to say that since no shipment can arrive prior to the shipments with the earliest arrival date, if they are the first shipments assigned, we can guarantee minimal lead-time, which helps in reducing wasted processing time.

EAD is approximately equivalent to the First Come First Served rule, which is intuitively a very efficient means of ensuring that the infrastructure is efficiently used. The primary failing of FCFS and EAD is relative to rules such as Shortest Processing Time or Weighted Shortest Processing Time. EAD is efficient at ensuring the maximum possible tonnage is carried, but does not account for weighting across tonnages. Fortunately, in our case, it is assumed that all shipments have equally inviolate priority.

The process of assignment for infrastructure is a relatively simple one. Each shipment is taken in order, and the algorithm searches the array to attempt to find space to unload it. At this point, we do not concern ourselves with vehicles. However, we do add the constraint that no shipment can be unloaded before its arrival time plus time of travel to the unloading point.

In order to search the array for the appropriate amount of time, we first calculate the time required for unloading. This is simply the size of the shipment divided by unloading capacity. We then find our start point, which is the arrival time for the shipment plus the travel time required on the mode in use. Finally, we iterate from this point to the deadline for the shipment, summing all free time we find.

The array of doubles used to track the amount of free infrastructure capacity is made up of double representations of the amount of capacity free on any given day. Each value is between 0 and 1. If the value is 0, the day is completely free. If the value is 1, the day is completely full. Any value other than these two represents a partially used day. The algorithm adds the remaining portion of the day for each day between the start time and the deadline, except the first. For that day, it adds the remainder only if the already allocated portion of the day is larger than travel time. This prevents the shipment from being treated as unloading while it is still in travel.

If the algorithm finds sufficient space for the unloading of the shipment, then the shipment is added to the output list for this mode. If it does not, then it is added to the output list for the next most expensive mode. It is not necessary at this stage for the loading to be contiguous, as the specifics of assignment are handled at the vehicle assignment stage.

### **Vehicle Assignment**

The vehicle assignment algorithm is the core of the scheduling heuristic. It receives a list of shipments which must be assigned to the most expensive mode from the infrastructure assignment component, and it converts that list into both a detailed schedule and a requirement in terms of number of vehicles. Because it is so essential, and because it is complex, it merits a more detailed look than either the deadline or infrastructure components of the heuristic.

The vehicle assignment algorithm uses the same method of selection for shipments as the infrastructure method. It chooses them based on earliest arrival date, tracking down through the assigned list, iterating each arrival date in turn.

Once the shipment has been chosen, the algorithm first determines the number of vehicles necessary to carry the shipment. This is the size of the shipment divided by the capacity of the vehicle, rounded upwards. The algorithm then begins the search for appropriate vehicle and unloading space for the shipment.

The first step in this process is identifying a free space on a vehicle. Much as in the infrastructure array, we use an array of doubles to track the usage of the vehicles. Unlike in the infrastructure array, however, we must seek to gain continuous use of the vehicle for the full duration of the trip. So rather than simply beginning at our starting point and proceeding to deadline, summing the free space, we use a rather more complicated summation process. We begin at the arrival day for the shipment and iterate through the chosen vehicle's days. If we find a day that is empty, we add 1 to our currently found free time. If we find a day that is not empty, we add the remainder of its capacity to our currently found free time. If, after adding the new capacity, the free time found is greater than the amount needed, we mark our original start time as an appropriate start time for the shipment-component and proceed to the infrastructure correction step. If not, we set our total free time equal to the remainder, and set the current day as our start time.

If we fail to identify a free spot large enough to carry the shipment and our vehicle isn't one that was generated just for this shipment, then we generate a new

vehicle to carry the shipment. If the vehicle was generated just for this shipment, then we ignore the deadline limitation and assign the shipment as late, if necessary.

If, however, we identify a free spot in the vehicles where the shipment could be carried, we must now confirm that there is infrastructure available to unload the shipment in the appropriate place. This process is identical to the process for finding free space on a vehicle, except that new infrastructure cannot be generated. If we find ourselves pushed past the deadline on infrastructure, we instead simply must assign past the deadline.

If the start time found by the vehicle-search is confirmed by the unload-search, then we may add it to our list and begin searching for vehicle and unload space for the next shipment-component. However, if it is not, we find the next start time available among the vehicles, starting at the one suggested by our unload-search. If the start time required correction, we repeat the process until the shipment is assigned.

If at any time we are forced to use a new vehicle, we track the number of this vehicle. The last vehicle we are forced to generate is the minimum number of vehicles required to service this set of requirements.

Finally, when we have found appropriate start times for all the components of a shipment, we allocate the shipment and fill the capacity in the unload and vehicle arrays. It is at this point that we remove the shipment from the shipment requirements array, to represent that it has been assigned.

### **Correction Step**

The correction step is the final process in the scheduling heuristic. In this stage, the algorithm uses the same search procedures used in the vehicle assignment stage, iterating through all unassigned shipments in EAD order. However, if it fails to find capacity, it simply moves on to the next shipment, rather than generating a new vehicle.

It treats the number of vehicles generated by the vehicle assignment step as a capacity on the amount of flow the vehicles are capable of handling. However, if a shipment can be assigned, it is assigned and deleted from the shipment list.



## **IV. Results and Analysis**

### **Simple Test Case**

In order to examine the capabilities of the algorithm, a series of test cases were created. The test cases were deliberately chosen for ease of solution, in order to make comparison against an intuitive or obvious perfect solution, simple for the reader. In the first case, our study case is hyper-simplified and consists of only 5 shipments, each with a three-day gap between arrival and delivery, arriving at the same source node, one per day, over a five day period, all of which are destined for the same sink node.

For simplicity's sake, this example deals in only one mode and the sizes of the five shipments are equal to the capacity of the vehicles, resulting in exactly one shipment being carried by each vehicle per trip. The vehicle was given a speed of 100, and the distance between nodes 1 and 2 was set to 100; also, the unloading capacity for the sink node was set to 100, to simplify displaying the outcome.

### 1. Simple Test Case Data Input

Shipment	Size	Source	Sink	Arrival	Deadline
1	100	1	2	1	4
2	100	1	2	2	5
3	100	1	2	3	6
4	100	1	2	4	7
5	100	1	2	5	8

The algorithm returned the following as a feasible resolution of the system, determining that the number of vehicles required for such a solution was three.

### 2. Simple Test Case Results Output

Shipment	Start Time	Arrival Time	Vehicle Number	Ahead of Deadline
1	1	4	1	Yes
2	2	5	2	Yes
3	3	6	3	Yes
4	4	7	1	Yes
5	5	8	2	Yes

Examining the above solution, it is possible to chart the assignments which each of the three vehicles had for the duration of the transportation solution; for clarity, the chart is shown below.

### 3. Simple Test Case Vehicle Schedule

Vehicle	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7
1	S1 delivery	S1 unload	S1 return	S4 delivery	S4 unload	S4 return	Idle
2	Idle	S2 delivery	S2 unload	S2 return	S5 delivery	S5 unload	S5 return
3	Idle	Idle	S3 delivery	S3 unload	S3 return	Idle	Idle

#### Modified Simple Case

The algorithm, then, is capable of achieving an intuitive result on a small scale. Given that this test case is equivalent to the case where all shipments can be carried on a single cheapest mode, that data shall not be repeated here. However, a secondary component of the algorithm which bears examination is its capacity to compensate for a shipment being forced onto a high cost mode, by utilizing the idle capacity of that mode to the greatest extent possible. As a consequence, our second test case, the modified simple case, will change the base case in two ways. First, it will add a second mode, considered more expensive than the first, which travels at a rate of 200 units per day, with identical independent unloading capacity to the first mode. Second, it will change the deadline on the first shipment to 2.

Because the first shipment has a deadline of 2, it is impossible for it to be delivered by the deadline using the first or second modes, and so it will be forced to travel on the second mode in order to minimize the violation of the deadline (guaranteeing a minimum number of vehicles for the second mode of at least one). However, the rest of the vehicle's time is not accounted for, and so we must allocate as

many shipments as possible to the idle time on that vehicle in order to minimize the number of lower cost vehicles used.

In this instance, the utilization of the mode allows for two additional shipments to be handled by the most expensive mode, on the same vehicle that is handling the first shipment, resulting in two fewer vehicles being required on the first mode.

#### 4. Modified Simple Case Data Input

Shipment	Size	Source	Sink	Deadline
S1	100	1	2	2
S2	100	1	2	5
S3	100	1	2	6
S4	100	1	2	7
S5	100	1	2	8

In this case, it is worth detailing the differences between the two modes, as well as their similarities:

#### 5. Modified Simple Case Vehicle Data

Vehicle	Capacity	Unload Rate	Speed
1	100	100	100
2	100	100	200

The chart of our delivery times, travel times, and vehicle pairings is given below, and below that, the chart of the vehicle time-assignments is given.

### 6. Modified Simple Case Shipment Schedule

Shipment	Start Time	Arrival Time	Vehicle Number	Ahead of Deadline
S1	1	2.5	1 (Mode 2)	No
S2	3	4.5	1 (Mode 2)	Yes
S3	3	5	1 (Mode 1)	Yes
S4	5	6.5	1 (Mode 2)	Yes
S5	6	8	1 (Mode 1)	Yes

Because the second mode performs deliveries in one half-day, the pattern is that on the 'outgoing' day, the travel is completed outgoing, and half of the unloading is done, and on the next day, the remainder of the unloading is completed, and then the shipment is returned.

### 7. Modified Simple Case Vehicle Schedule

Vehicle	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day7
1 (Mode 2)	S1 Out	S1 Return	S2 Out	S2 Return	S4 Out	S4 Return	Idle
1 (Mode 1)	Idle	Idle	S3 Out	S3 Deliver	S3 Return	S5 Out	S5 Deliver

This demonstrates the capacity of the algorithm to combine minimization techniques in order to reduce the impact of forced increases in the number of high-cost vehicles being deployed, by utilizing those new, largely idle, vehicles in order to decrease

the number of vehicles required at lower tiers. Of course, in a more complex problem, resolutions will be substantially more complicated to come by, and in most cases, less efficient, and less obviously so. However, the general principle of efficient allocation still holds in more complex cases.

### **Multinodal, Multimodal Demonstration Case**

The complexity of the algorithm, and its potency, rests upon its capacity to deal efficiently, and quickly, with problems that handle both multiple sources and sinks, and multiple modes, on large scale, but of course it is difficult to demonstrate efficiency in the large scale, because by-hand and intuitive solutions are hard to come by. Instead, we examine the efficacy of the algorithm using a smaller multimodal, multinodal pattern.

In this instance, our case involves three modes, over four nodes, each equidistant at 100 units from each other node, and each capable of unloading 100 units per day from each mode. For this problem, the speeds for our three vehicle types are 50, 100, and 200 units and the capacities are the same. We will process twelve shipments across the nodes, using nodes 1 and 2 solely as sources, and nodes 3 and 4 solely as sinks. The sum of all tonnage shipped is 2400 and the arrival times and deadlines are broadly separated, allowing for a powerful estimate of  $2400/10$  or 240 tons per day of shipping power being a floor on the number of tons per day of vehicle required to handle the shipping.

Of course, at this tier of processing, the outputs become significantly more complicated. As a consequence, we will simply list the vehicle number, node, start time, and mode for each shipment and shipment-component.

## 8. Multimodal Simple Case Data Input

Shipment No.	Source	Sink	Size	Arrival	Deadline
1	1	3	100	1	7
2	2	3	200	1	7
3	1	4	300	1	7
4	2	4	100	1	7
5	1	3	200	3	10
6	2	3	300	3	10
7	1	4	100	3	10
8	2	4	200	3	10
9	1	3	300	1	7
10	2	3	100	1	7
11	1	4	200	3	10
12	2	4	300	3	10

This list is not the original data output from the program, but has been sorted to highlight both the process behind the assignment of shipments to specific vehicles and a problem induced by the specific granularity of the shipments. Note that the shipments fit neatly together, as regards unloading. This is due to the algorithm's deliberate seeking of gaps at every stage of a schedule's creation, resulting in carefully stacked shipment unloading times. Of course, this method is aided by the uniformity of vehicle unload-times, which are in the algorithm artificially held constant, as a relationship between the size of vehicle, and the capacity for unloading that particular vehicle at that particular node. Nonetheless, the algorithm has finely used all available unloading space in this limited example.

A notable, potential error is the double-booking effect visible in the use of mode 2, node 3 unloading capacity. Shipment-components are being loaded simultaneously, resulting in unloading times taking up the same block, theoretically. This, of course, is an

impossibility according to the strict rules of the problem. The shipments, according to our previous assumptions, use all unloading capacity totally and therefore cannot be unloaded simultaneously.

The cause of this apparent error is double-booking. The shipments are both attempting to use the latter half of the first day on which they both arrive, and the first half of the next day. As the algorithm does not have sufficient granularity to track half-days, the shipments are nominally double-booking.

The next table shows the data with a view to the particular assignments made to specific vehicles at specific times. Notably, it sorts by mode, then vehicle number, and then start-time, in order to demonstrate the relative efficiency and inefficiency of allocation according to the algorithm.

In this case, the algorithm generates an essentially perfect solution to the system, using virtually every open space, and the result is intuitively near-optimal. For mode 1, each vehicle can handle at most 3 assignments (as it requires three days to deliver any in particular, and the latest deadline is day 10). From this we know that, at least, we would need 5 vehicles, as we have 14 shipments. Shipment 7, our last shipment, has a deadline on day 7, and so it is apparent it could not easily be transferred to vehicle 4 or 5 with the shipment loads as they currently stand. While it is conceivable that a more efficient solution exists, the solution generated by the algorithm is intuitively near-optimal, at least for mode 1. On mode 2, we simply observe that both vehicles are identically full.



### 9. Multimodal Simple Case Shipment Output

Shipment	Vehicle	Start Time	Mode	Sink
2	1	1	1	3
2	1	4	1	3
8	1	7	1	4
3	2	1	1	4
3	2	4	1	4
8	2	8	1	4
3	3	2	1	4
4	3	5	1	4
11	3	9	1	4
9	4	2	1	3
9	4	5	1	3
9	5	3	1	3
11	5	6	1	4
7	6	3	1	4
10	1	1	2	3
6	1	3	2	3
6	1	5	2	3
6	1	7	2	3
12	1	9	2	4
1	2	1	2	3
12	2	3	2	4
12	2	5	2	4
5	2	7	2	3
5	2	9	2	3

To compare to our earlier values, we have 6 vehicles of type 1, shipping 100 units every 3 days, and 2 vehicles of type 2, shipping 100 units every 2 days, for a total of 300 units of shipping capacity. This compares favorably to our lower bound estimate of 240 tons as an absolute minimum, given the effects of infrastructure interference and the uneven effect of making trips of duration 3 days during a space of 10 days.

## **Multimodal Large Scale Case**

In order to test the algorithm's capacity to perform at large scale, a new shipping requirement list was created for the multimodal simple case. In this expansion of the original problem, we extrapolated the original data set to one hundred shipments, and extended the infrastructure capacity of the underlying network to handle 100,000 units per node per day, in order to ensure feasibility.

Solution of the problem required approximately five seconds. The data that was returned indicated that 212 vehicles were required to handle the shipping, all of the same mode, which approximately conforms to expectations. Given that infrastructure and deadline limitations were not concerns, all shipments should have been processed on the first mode. This was indeed the case.

Determining whether the solution was ultimately feasible would require detailed comparison of each shipment to each other shipment and to the overall infrastructure capacity and vehicle usage charts, in order to confirm the validity of the original result, but a superficial examination reveals start times which increase slowly as the infrastructure begins to fill.

A second attempt was made to process the same set of shipments, using infrastructure of only 100 per day. This resulted in massive over-flow, as predicted, overflowing the limited 2-dimensional array for unloading.

## Appendix A: Shortest Path Network Generator

```
Sub simplifynetwork()  
    Dim n As Integer  
    Dim i As Integer  
    Dim SourceNode As Integer  
    Dim NetworkSheet As String  
    Dim numnodes As Integer  
    NetworkSheet = ActiveSheet.Name  
    SourceNode = 1  
    n = 1  
    i = 1  
    j = 1  
    Sheets(NetworkSheet).Activate  
    Range("A1").Select  
    Do While ActiveCell.Offset(n, 0).Value <> 0  
        n = n + 1  
    Loop  
    numnodes = n - 1  
    Sheets.Add.Name = "Simplified " & NetworkSheet  
    Sheets.Add.Name = "Simplified " & NetworkSheet & " Paths"  
    Do While SourceNode <= numnodes  
        DijkstrasAlgorithm SourceNode, numnodes, NetworkSheet  
        SourceNode = SourceNode + 1  
    Loop  
    Sheets("Simplified " & NetworkSheet & " Paths").Activate
```

```
ActiveCell.Value = "Nodes"

Do While i <= numnodes

    ActiveCell.Offset(0, i) = Str(i)

    ActiveCell.Offset(i, 0) = Str(i)

    i = i + 1

Loop

Sheets("Simplified " & NetworkSheet).Activate

ActiveCell.Value = "Nodes"

Do While j <= numnodes

    ActiveCell.Offset(0, j) = Str(j)

    j = j + 1

Loop

End Sub
```

```
Sub DijkstrasAlgorithm(SourceNode As Integer, numnodes As Integer, NetworkSheet As String)
```

```
    Dim CurrentNode As Integer
```

```
    Dim CurrentDist As Double
```

```
    Dim AmDone As Boolean
```

```
    Dim ShortestDist() As Double
```

```
    Dim BigM As Double
```

```
    Dim n As Integer
```

```
    Dim i As Integer
```

```
    Dim j As Integer
```

```
    Dim CurrentLowDist As Double
```

```
    Dim CurrentLowNode As Integer
```

```
    Dim FoundUnexplored As Boolean
```

```
    Dim K As Integer
```

```
    Dim DistOnThisPath As Double
```

```
    Dim ShortestPath() As String
```

```
    Dim p As Integer
```

```
    AmDone = False
```

```
    CurrentNode = SourceNode
```

```
    CurrentDist = 0
```

```
    BigM = 1E+300
```

```
    n = 1
```

```
    ReDim ShortestDist(1 To numnodes)
```

```
    ReDim ShortestPath(1 To numnodes)
```

```
    Do While n <= numnodes
```

```
        ShortestDist(n) = BigM
```

```

ShortestPath(n) = Str(SourceNode)

n = n + 1

Loop
ShortestDist(SourceNode) = 0

Do While AmDone = False

    i = 1

    Do While i <= numnodes

        DistOnThisPath = finddist(CurrentNode, i, NetworkSheet) +
ShortestDist(CurrentNode)

        If DistOnThisPath < ShortestDist(i) Then

            ShortestDist(i) = DistOnThisPath

            ShortestPath(i) = ShortestPath(CurrentNode) & Str(i)

        End If

        i = i + 1

    Loop

    j = 1

    CurrentLowDist = BigM

    FoundUnexplored = False

    Do While j <= numnodes

        If ShortestDist(j) > CurrentDist Then

            If ShortestDist(j) < CurrentLowDist Then

                CurrentLowDist = ShortestDist(j)

                CurrentLowNode = j

                FoundUnexplored = True

            End If

        ElseIf ShortestDist(j) = CurrentDist Then

            If CurrentNode < j Then

```

```

        CurrentLowDist = ShortestDist(j)

        CurrentLowNode = j

        FoundUnexplored = True

    End If

End If

j = j + 1

Loop

If FoundUnexplored = False Then

    AmDone = True

ElseIf FoundUnexplored = True Then

    CurrentNode = CurrentLowNode

    CurrentDist = CurrentLowDist

End If

Loop

Sheets("Simplified " & NetworkSheet).Activate

ActiveSheet.Range("A1").Select

K = 1

Do While ActiveCell.Offset(K, 0).Value <> 0

    K = K + 1

Loop

ActiveCell.Offset(K, 0) = SourceNode

l = 1

Do While l < numnodes + 1

    ActiveCell.Offset(K, l) = ShortestDist(l)

    l = l + 1

Loop

```

```

Sheets("Simplified " & NetworkSheet & " Paths").Activate
ActiveSheet.Range("A1").Select
p = 1
Do While p < numnodes + 1
    ActiveCell.Offset(K, p) = ShortestPath(p)
    p = p + 1
Loop
End Sub

Function finddist(SourceNode As Integer, sinknode As Integer, NetworkSheet As String)
    Sheets(NetworkSheet).Activate
    ActiveSheet.Range("A1").Select
    finddist = CDBl(ActiveCell.Offset(SourceNode, sinknode).Value)
End Function

```



## **Appendix B: Ordered Scheduling Heuristic**

Public NumNodes As Integer  
Public NumModes As Integer  
Public numshipments As Integer  
Public SimpleNetwork() As Variant  
Public minvehicles() As Integer  
Public latedeadline As Integer  
Public highestused As Integer  
Public ShArrival() As Variant  
Public ShDeadline() As Variant  
Public vehiclespeeds() As Variant  
Public shsize As Variant  
Public shsink As Variant  
Public shsource As Variant  
Public vcapacity As Variant  
Public shUnloadTime() As Double  
Public shipmentarray() As Integer  
Public shipmentarraynum As Integer  
Public vunloadtime() As Double  
Public index As Integer  
Public shtraveltime() As Double

```

Sub HeuristicScheduler()
    Dim NumShipArray As Integer
    Dim DeadlineArray() As Integer
    Dim DeadlineTracker() As Integer
    Dim infraarray() As Integer
    Dim infratracker() As Integer
    Dim n As Integer
    Dim mode As Integer
    Popglobals
    PopulateSimpleNetwork
    index = 1
    ReDim shUnloadTime(1 To NumModes, 1 To numshipments)
    ReDim shipmentarray(1 To numshipments)
    shipmentarraynum = numshipments
    n = 1
    Do While n <= numshipments
        shipmentarray(n) = n
        n = n + 1
    Loop
    mode = NumModes
    Do While mode > 0
        DeadlineArrayGenerator shipmentarray(), shipmentarraynum, DeadlineArray(),
DeadlineTracker()
        InfraArrayGenerator DeadlineArray(), DeadlineTracker(), infraarray(), infratracker()
        ListVehicAssign infraarray(), infratracker(), mode
    Loop
End Sub

```

```
eliminateshipments infraarray(), infratracker(), mode, shipmentarray(),  
shipmentarraynum
```

```
mode = mode - 1
```

```
Loop
```

```
End Sub
```

```
Sub eliminateshipments(infraarray() As Integer, infratracker() As Integer, mode As Integer, shipmentarray() As Integer, shipmentarraynum As Integer)
```

```
    Dim n As Integer
```

```
    Dim k As Integer
```

```
    Dim elim As Boolean
```

```
    elim = False
```

```
    n = 1
```

```
    k = 1
```

```
    Do While n <= infratracker(mode)
```

```
        Do While k <= shipmentarraynum And elim = False
```

```
            If infraarray(mode, n) = shipmentarray(k) Then
```

```
                elim = True
```

```
                shipmentarray(k) = shipmentarray(shipmentarraynum)
```

```
                shipmentarraynum = shipmentarraynum - 1
```

```
            End If
```

```
            k = k + 1
```

```
        Loop
```

```
        elim = False
```

```
        k = 1
```

```
        n = n + 1
```

```
    Loop
```

```
End Sub
```

```

Sub ListVehicAssign(infraarray() As Integer, infratracker() As Integer, mode As Integer)

    Dim n As Integer

    Dim VehicAssignArray() As Double

    Dim unloadarray() As Double

    Dim currmode As Integer

    ReDim VehicAssignArray(1 To minvehicles(mode), 1 To latedeadline)

    ReDim unloadarray(1 To NumNodes, 1 To latedeadline)

    highestused = 0

    n = 1

    Do While n <= infratracker(mode)

        ShipmentVehicAssign VehicAssignArray(), infraarray(mode, n), mode,
unloadarray(), highestused

        n = n + 1

    Loop

    minvehicles(mode) = highestused

    If mode > 1 Then

        listgapcheck VehicAssignArray(), infraarray(), infratracker(mode - 1), mode,
unloadarray()

    End If

End Sub

```

```
Sub listgapcheck(VehicAssignArray() As Double, ShipmentList() As Integer, infranum  
As Integer, currmode As Integer, unloadarray() As Double)  
  
    Dim n As Integer  
  
    Dim found As Boolean  
  
    Dim currvehicle As Integer  
  
    n = 1  
  
    Do While n <= infranum  
  
        ShipmentGapCheck VehicAssignArray(), ShipmentList(), n, infranum, currmode,  
unloadarray()  
  
        n = n + 1  
  
    Loop  
  
End Sub
```

```
Sub ShipmentGapCheck(VehicAssignArray() As Double, ShipmentList() As Integer,  
ShipmentNumber As Integer, infranum As Integer, mode As Integer, unloadarray() As  
Double)
```

```
    Dim currvehicle As Integer
```

```
    Dim found As Boolean
```

```
    Dim currstart As Double
```

```
    Dim starttimes() As Double
```

```
    Dim foundvehicles As Integer
```

```
    Dim vehicles() As Integer
```

```
    Dim shipment As Integer
```

```
    Dim i As Integer
```

```
    Dim j As Integer
```

```
    Dim elim As Boolean
```

```
    Dim pseudounloadarray() As Double
```

```
    Dim l As Integer
```

```
    Dim k As Integer
```

```
    Dim traveltime As Double
```

```
    ReDim pseudounloadarray(1 To NumNodes, 1 To latedeadline)
```

```
    shipment = ShipmentList(mode - 1, ShipmentNumber)
```

```
    traveltime = SimpleNetwork(mode)(shsource(shipment), shsink(shipment)) /  
vehiclespeeds(mode)
```

```
    currvehicle = 1
```

```
    l = 1
```

```
    k = 1
```

```
    Do While l <= NumNodes
```

```
        Do While k <= latedeadline
```

```
            pseudounloadarray(l, k) = unloadarray(l, k)
```

```

    k = k + 1

Loop
k = 1
l = l + 1
Loop
If shsize(shipment) / vcapacity(mode) - Int(shsize(shipment) / vcapacity(mode)) > 0
Then
    neededvehicles = Int(shsize(shipment) / vcapacity(mode)) + 1
Else
    neededvehicles = Int(shsize(shipment) / vcapacity(mode))
End If
ReDim vehicles(1 To neededvehicles)
ReDim starttimes(1 To neededvehicles)
Do While currvehicle <= minvehicles(mode) And foundvehicles < neededvehicles
    If foundvehicles > 0 Then
        If vehicles(foundvehicles) = currvehicle Then
            currstart = starttimes(foundvehicles) + vunloadtime(mode, shsink(shipment)) +
2 * SimpleNetwork(mode)(shsource(shipment), shsink(shipment)) / vehiclespeeds(mode)
        Else
            currstart = 0
        End If
    Else
        currstart = 0
    End If
    found = True
    corrected = True
    Do While found = True And corrected = True

```



found = findstarttime(VehicAssignArray(), mode, starttimes(foundvehicles + 1),  
currvehicle, currstart, shipment)

corrected = correctstarttime(pseudounloadarray(), mode, starttimes(foundvehicles  
+ 1), currvehicle, found, shipment, currstart)

Loop

If found = True Then

foundvehicles = foundvehicles + 1

allocate starttimes(foundvehicles) + traveltime, pseudounloadarray(),  
shsink(shipment), vunloadtime(mode, shsink(shipment))

vehicles(foundvehicles) = currvehicle

n = n + 1

Else

currvehicle = currvehicle + 1

corrected = True

found = True

End If

Loop

i = 1

If foundvehicles >= neededvehicles Then

Do While i <= neededvehicles

allocshipvehic starttimes(i), vehicles(i), shipment, VehicAssignArray(),  
unloadarray(), mode

i = i + 1

Loop

j = 1

Do While j <= infranum And elim = False

If shipmentarray(j) = shipment Then

shipmentarray(j) = shipmentarray(shipmentarraynum)

```
shipmentarraynum = shipmentarraynum - 1  
elim = True  
End If  
j = j + 1  
Loop  
End If  
End Sub
```

```
Sub ShipmentVehicAssign(VehicAssignArray() As Double, shipment As Integer, mode  
As Integer, unloadarray() As Double, highestused As Integer)
```

```
    Dim neededvehicles As Integer
```

```
    Dim n As Integer
```

```
    Dim i As Integer
```

```
    Dim starttimes() As Double
```

```
    Dim found As Boolean
```

```
    Dim corrected As Boolean
```

```
    Dim currstart As Double
```

```
    Dim vehicles() As Integer
```

```
    Dim currvehicle As Integer
```

```
    Dim pseudounloadarray() As Double
```

```
    Dim j As Integer
```

```
    Dim k As Integer
```

```
    Dim temphighestused As Integer
```

```
    Dim traveltime As Double
```

```
    ReDim pseudounloadarray(1 To NumNodes, 1 To latedeadline)
```

```
    traveltime = SimpleNetwork(mode)(shsource(shipment), shsink(shipment)) /  
vehiclespeeds(mode)
```

```
    j = 1
```

```
    k = 1
```

```
    Do While j <= NumNodes
```

```
        Do While k <= latedeadline
```

```
            pseudounloadarray(j, k) = unloadarray(j, k)
```

```
            k = k + 1
```

```
        Loop
```

```

    k = 1
    j = j + 1
Loop
    If shsize(shipment) / vcapacity(mode) - Int(shsize(shipment) / vcapacity(mode)) > 0
Then
        neededvehicles = Int(shsize(shipment) / vcapacity(mode)) + 1
    Else
        neededvehicles = Int(shsize(shipment) / vcapacity(mode))
    End If
    ReDim starttimes(1 To neededvehicles)
    ReDim vehicles(1 To neededvehicles)
    n = 1
    currvehicle = 1
    temphighestused = highestused
    Do While n <= neededvehicles
        corrected = True
        found = True
        If foundvehicles > 0 Then
            If vehicles(foundvehicles) = currvehicle Then
                currstart = starttimes(foundvehicles) + vunloadtime(mode, shsink(shipment)) +
2 * SimpleNetwork(mode)(shsource(shipment), shsink(shipment)) / vehiclespeeds(mode)
            Else
                currstart = 0
            End If
        Else
            currstart = 0
        End If
    End While

```

```

Do While corrected = True And found = True

    found = findstarttime(VehicAssignArray(), mode, starttimes(n), currvehicle,
currstart, shipment)

    corrected = correctstarttime(pseudounloadarray(), mode, starttimes(n),
currvehicle, found, shipment, currstart)

    Loop

    If found = True Or currvehicle > temphighestused Then

        vehicles(n) = currvehicle

        foundvehicles = foundvehicles + 1

        allocate starttimes(n) + traveltime, pseudounloadarray(), shsink(shipment),
vunloadtime(mode, shsink(shipment))

        If vehicles(foundvehicles) > temphighestused Then

            temphighestused = vehicles(foundvehicles)

        End If

        n = n + 1

    Else

        currvehicle = currvehicle + 1

        currstart = 0

        corrected = True

        found = True

    End If

    Loop

    i = 1

    Do While i <= neededvehicles

        If shipment = 3 Then

            shipment = shipment

        End If

```

```
    allocshipvehic starttimes(i), vehicles(i), shipment, VehicAssignArray(),  
    unloadarray(), mode
```

```
    i = i + 1
```

```
Loop
```

```
If vehicles(neededvehicles) > highestused Then
```

```
    highestused = vehicles(neededvehicles)
```

```
End If
```

```
End Sub
```

```
Sub allocshipvehic(starttime As Double, vehicle As Integer, shipment As Integer,  
VehicAssignArray() As Double, unloadarray() As Double, mode As Integer)
```

```
    Dim reqvehictime As Double
```

```
    Dim requnloadtime As Double
```

```
    Dim allocvehictime As Double
```

```
    Dim allocunloadtime As Double
```

```
    Dim currtime As Double
```

```
    Dim timetransfervariable As Double
```

```
    Dim currday As Integer
```

```
    Sheets("Output").Range("A1").Offset(index, 0) = shipment
```

```
    Sheets("Output").Range("A1").Offset(index, 1) = vehicle
```

```
    Sheets("Output").Range("A1").Offset(index, 2) = starttime
```

```
    Sheets("Output").Range("A1").Offset(index, 3) = mode
```

```
    Sheets("Output").Range("A1").Offset(index, 4) = shsink(shipment)
```

```
    index = index + 1
```

```
    reqvehictime = SimpleNetwork(mode)(shsource(shipment), shsink(shipment)) /  
    vehiclespeeds(mode) * 2 + vunloadtime(mode, shsink(shipment))
```

```
    requnloadtime = vunloadtime(mode, shsink(shipment))
```

```
    currday = Int(starttime)
```

```
    allocvehictime = 0
```

```
    Do While allocvehictime < reqvehictime
```

```
        timetransfervariable = 1
```

```
        If timetransfervariable > (1 - starttime + currday) Then
```

```
            timetransfervariable = 1 - starttime + currday
```

```
        End If
```

```
        If timetransfervariable > 1 - VehicAssignArray(vehicle, currday) Then
```

```

    timetransfervariable = 1 - VehicAssignArray(vehicle, currday)
End If

If timetransfervariable > reqvehictime - allocvehictime Then

    timetransfervariable = reqvehictime - allocvehictime

End If

VehicAssignArray(vehicle, currday) = VehicAssignArray(vehicle, currday) +
timetransfervariable

allocvehictime = allocvehictime + timetransfervariable

currday = currday + 1

Loop

currday = Int(starttime + SimpleNetwork(mode)(shsource(shipment),
shsink(shipment)) / vehiclespeeds(mode))

Do While allocunloadtime < requnloadtime

    timetransfervariable = requnloadtime - allocunloadtime

    If timetransfervariable > (1 - starttime - SimpleNetwork(mode)(shsource(shipment),
shsink(shipment)) / vehiclespeeds(mode) + currday) Then

        timetransfervariable = (1 - starttime - SimpleNetwork(mode)(shsource(shipment),
shsink(shipment)) / vehiclespeeds(mode) + currday)

    End If

    If timetransfervariable > 1 - unloadarray(shsink(shipment), currday) Then

        timetransfervariable = 1 - unloadarray(shsink(shipment), currday)

    End If

    unloadarray(shsink(shipment), currday) = unloadarray(shsink(shipment), currday) +
timetransfervariable

    allocunloadtime = allocunloadtime + timetransfervariable

    currday = currday + 1

Loop

End Sub

```



Function correctstarttime(infraassignarray() As Double, mode As Integer, starttime As Double, currvehicle As Integer, found As Boolean, shipment As Integer, currstart As Double)

Dim currunloadtime As Double

Dim currday As Integer

Dim traveltime As Double

Dim availtime As Double

Dim curravailtime As Double

traveltime = SimpleNetwork(mode)(shsource(shipment), shsink(shipment)) /  
vehiclespeeds(mode)

currunloadtime = starttime + traveltime

currday = Int(currunloadtime)

Do While availtime < vunloadtime(mode, shsink(shipment)) And currday <  
latedeadline

curravailtime = 1

If 1 - infraassignarray(shsink(shipment), currday) < curravailtime Then

curravailtime = 1 - infraassignarray(shsink(shipment), currday)

End If

If 1 - (currunloadtime - currday) < curravailtime Then

curravailtime = 1 - (currunloadtime - currday)

End If

availtime = availtime + curravailtime

If infraassignarray(shsink(shipment), currday) > 0 And availtime <  
vunloadtime(mode, shsink(shipment)) Then

currunloadtime = currday + infraassignarray(shsink(shipment), currday)

currday = currday + 1

availtime = currday - currunloadtime

End If

```

Loop
  If currunloadtime = starttime + traveltime Then
    correctstarttime = False
  Else
    correctstarttime = True
    currstart = currunloadtime - traveltime
  End If

  If availtime >= vunloadtime(mode, shsink(shipment)) And currunloadtime +
  vunloadtime(mode, shsink(shipment)) <= ShDeadline(shipment) + 1 Then
    found = True
  Else
    found = False
  End If
End Function

```

Function findstarttime(VehicAssignArray() As Double, mode As Integer, starttime As Double, currvehicle As Integer, currstart As Double, shipment As Integer)

Dim currtime As Double

Dim currday As Integer

Dim reqtime As Double

Dim availtime As Double

Dim curravailtime As Double

If ShArrival(shipment) > currstart Then

currtime = ShArrival(shipment)

Else

currtime = currstart

End If

currday = Int(currtime)

reqtime = SimpleNetwork(mode)(shsource(shipment), shsink(shipment)) /  
vehiclespeeds(mode) \* 2 + vunloadtime(mode, shsink(shipment))

Do While availtime < reqtime And currday < latedeadline

curravailtime = 1

If 1 - VehicAssignArray(currvehicle, currday) < curravailtime Then

curravailtime = 1 - VehicAssignArray(currvehicle, currday)

End If

If 1 - (currtime - currday) < curravailtime Then

curravailtime = 1 - (currtime - currday)

End If

availtime = availtime + curravailtime

If VehicAssignArray(currvehicle, currday) > 0 And availtime < reqtime Then

availtime = 1 - VehicAssignArray(currvehicle, currday)

```

        currtime = currday + VehicAssignArray(currvehicle, currday)
    End If

    currday = currday + 1

Loop

starttime = currtime

    If availtime >= reqtime And starttime + SimpleNetwork(mode)(shsource(shipment),
shsink(shipment)) / vehiclespeeds(mode) + vunloadtime(mode, shsink(shipment)) <
ShDeadline(shipment) + 1 Then

        findstarttime = True

    Else

        findstarttime = False

    End If

End Function

```

```

Sub InfraArrayGenerator(DeadlineArray() As Integer, DeadlineTracker() As Integer,
infraarray() As Integer, infratracker() As Integer)

    Dim n As Integer

    ReDim infraarray(1 To NumModes, 1 To numshipments)
    ReDim infratracker(1 To NumModes)

    n = 1

    Do While n <= NumModes
        InfraAssignStep DeadlineArray(), DeadlineTracker(), infraarray(), infratracker(), n
        n = n + 1
    Loop
End Sub

```

```

Sub InfraAssignStep(DeadlineArray() As Integer, DeadlineTracker() As Integer,
infraarray() As Integer, infratracker() As Integer, currmode As Integer)

    Dim infraassignarray() As Double

    Dim n As Integer

    Dim currarrival As Integer

    Dim i As Integer

    Dim shipment As Integer

    ReDim shtraveltime(1 To numshipments)

    ShDeadline =
Application.WorksheetFunction.Transpose(Sheets("Shipments").Range("F2",
Sheets("Shipments").Range("F2").End(xlDown)))

    ShArrival =
Application.WorksheetFunction.Transpose(Sheets("Shipments").Range("E2",
Sheets("Shipments").Range("E2").End(xlDown)))

    shsink = Application.WorksheetFunction.Transpose(Sheets("Shipments").Range("C2",
Sheets("Shipments").Range("C2").End(xlDown)))

    populatetraveltime currmode, shtraveltime(), shsink

    n = 1

    latedeadline = 0

    Do While n <= numshipments

        If ShDeadline(n) > latedeadline Then

            latedeadline = ShDeadline(n)

        End If

        If ShArrival(n) > latearrival Then

            latearrival = ShArrival(n)

        End If

        n = n + 1

    Loop

```

```

latedeadline = latedeadline * 2

ReDim infraassignarray(1 To NumNodes, 1 To latedeadline)

i = 1

currarrival = 1

Do While currarrival <= latearrival

    Do While i <= DeadlineTracker(currmode)

        shipment = DeadlineArray(currmode, i)

        If currarrival = ShArrival(shipment) Then

            found = findspace(shipment, infraassignarray(), shtraveltime(shipment) +
ShArrival(shipment), ShDeadline(shipment), shsink(shipment),
shUnloadTime(currmode, shipment))

            If found = True Or currmode = NumModes Then

                allocate ShArrival(shipment) + shtraveltime(shipment), infraassignarray(),
shsink(shipment), shUnloadTime(currmode, shipment)

                infratracker(currmode) = infratracker(currmode) + 1

                infraarray(currmode, infratracker(currmode)) = DeadlineArray(currmode, i)

                found = False

            Else

                DeadlineTracker(currmode + 1) = DeadlineTracker(currmode + 1) + 1

                DeadlineArray(currmode + 1, DeadlineTracker(currmode + 1)) =
DeadlineArray(currmode, i)

            End If

        End If

        i = i + 1

    Loop

    i = 1

    currarrival = currarrival + 1

```

```
Loop  
End Sub
```



```

Sub populatetraveltime(mode As Integer, traveltime() As Double, sink As Variant)

    Dim n As Integer

    vehiclespeeds =
Application.WorksheetFunction.Transpose(Sheets("Vehicles").Range("B2",
Sheets("Vehicles").Range("B2").End(xlDown)))

    shsource =
Application.WorksheetFunction.Transpose(Sheets("Shipments").Range("B2",
Sheets("Shipments").Range("B2").End(xlDown)))

    n = 1

    Do While n <= numshipments

        traveltime(n) = SimpleNetwork(mode)(shsource(n), sink(n)) / vehiclespeeds(mode)

        n = n + 1

    Loop

    n = 1

End Sub

```

```

Sub populateneededtime(mode As Integer, sink As Variant)

    Dim n As Integer

    Dim infraarray() As Variant

    Dim transfervariable As Variant

    Dim j As Integer

    Dim k As Integer

    ReDim infraarray(1 To NumModes)

    ReDim vunloadtime(1 To NumModes, 1 To NumNodes)

    shsize = Application.WorksheetFunction.Transpose(Sheets("Shipments").Range("D2",
    Sheets("Shipments").Range("D2").End(xlDown)))

    j = 1

    Do While j <= NumModes

        With Sheets("Network " & j & " Infra").Range("B2")

            transfervariable = Application.WorksheetFunction.Transpose(Range(.Offset(0, 0),
            .End(xlDown)))

        End With

        infraarray(j) = transfervariable

        k = 1

        Do While k <= NumNodes

            vunloadtime(j, k) = vcapacity(mode) / infraarray(j)(k)

            k = k + 1

        Loop

        j = j + 1

    Loop

    n = 1

    Do While n <= numshipments

```

```
shUnloadTime(mode, n) = shsize(n) / infraarray(mode)(sink(n))  
n = n + 1  
Loop  
End Sub
```

```
Function findspace(shipment As Integer, infraassignarray() As Double, startpoint As Double, deadline As Variant, sink As Variant, neededtime As Double)
```

```
    Dim foundtime As Double
```

```
    Dim currday As Integer
```

```
    currday = Int(startpoint)
```

```
    Do While foundtime < neededtime And currday <= deadline
```

```
        foundtime = 1 - infraassignarray(sink, currday) + foundtime
```

```
        If 1 - (startpoint - currday) < foundtime Then
```

```
            foundtime = 1 - (startpoint - currday)
```

```
        End If
```

```
        currday = currday + 1
```

```
    Loop
```

```
    If foundtime >= neededtime Then
```

```
        findspace = True
```

```
    Else
```

```
        findspace = False
```

```
    End If
```

```
End Function
```

```
Sub allocate(startpoint As Double, infraassignarray() As Double, sink As Variant,  
neededtime As Double)
```

```
    Dim remainingtime As Double
```

```
    Dim currday As Integer
```

```
    Dim transfertime As Double
```

```
    currday = Int(startpoint)
```

```
    remainingtime = neededtime
```

```
    Do While remainingtime > 0
```

```
        transfertime = remainingtime
```

```
        If transfertime > 1 - infraassignarray(sink, currday) Then
```

```
            transfertime = 1 - infraassignarray(sink, currday)
```

```
        End If
```

```
        If transfertime > currday + 1 - startpoint Then
```

```
            transfertime = currday + 1 - startpoint
```

```
        End If
```

```
        infraassignarray(sink, currday) = infraassignarray(sink, currday) + transfertime
```

```
        remainingtime = remainingtime - transfertime
```

```
        currday = currday + 1
```

```
    Loop
```

```
End Sub
```

Sub Popglobals()

Dim vehicleestimate As Integer

Dim i As Integer

Dim mode As Integer

numshipments = Sheets("Shipments").Range("A1",  
Sheets("Shipments").Range("A1").End(xlDown)).Rows.Count - 1

NumModes = Sheets("Vehicles").Range("A1",  
Sheets("Vehicles").Range("A1").End(xlDown)).Rows.Count - 1

NumNodes = Sheets("Simplified Network 1").Range("A1", Sheets("Simplified  
Network 1").Range("A1").End(xlDown)).Rows.Count - 1

shsize = Application.WorksheetFunction.Transpose(Sheets("Shipments").Range("D2",  
Sheets("Shipments").Range("D2").End(xlDown)))

vcapacity =  
Application.WorksheetFunction.Transpose(Sheets("Vehicles").Range("C2",  
Sheets("Vehicles").Range("C2").End(xlDown)))

vehicleestimate = 0

i = 1

mode = 1

ReDim minvehicles(1 To NumModes)

Do While mode <= NumModes

Do While i <= numshipments

If shsize(i) / vcapacity(mode) > 1 Then

vehicleestimate = vehicleestimate + shsize(i) / vcapacity(mode)

Else

vehicleestimate = vehicleestimate + 1

End If

i = i + 1

Loop

```
i = 1  
minvehicles(mode) = Int(vehicleestimate * 2)  
mode = mode + 1  
vehicleestimate = 0  
Loop  
End Sub
```

```

Sub DeadlineArrayGenerator(shipmentarray() As Integer, NumShipArray As Integer,
DeadlineArray() As Integer, DeadlineTracker() As Integer)

    Dim n As Integer
    Dim mode As Integer
    Dim FeasArray() As Integer
    ReDim DeadlineArray(1 To NumModes, 1 To NumShipArray)
    ReDim DeadlineTracker(1 To NumModes)
    ReDim FeasArray(1 To numshipments)
    n = 1
    DetFeas FeasArray()
    Do While n <= NumShipArray
        mode = FeasArray(shipmentarray(n))
        DeadlineTracker(mode) = DeadlineTracker(mode) + 1
        DeadlineArray(mode, DeadlineTracker(mode)) = shipmentarray(n)
        n = n + 1
    Loop
End Sub

```



```

Sub DetFeas(FeasArray() As Integer)

    Dim shsource As Variant

    Dim shsink As Variant

    Dim ShArrival As Variant

    Dim ShDeadline As Variant

    Dim vehiclespeeds As Variant

    Dim found As Boolean

    Dim n As Integer

    Dim k As Integer

    Dim i As Integer

    ReDim FeasArray(1 To numshipments)

    shsource =
Application.WorksheetFunction.Transpose(Sheets("Shipments").Range("B2",
Sheets("Shipments").Range("B2").End(xlDown)))

    shsink = Application.WorksheetFunction.Transpose(Sheets("Shipments").Range("C2",
Sheets("Shipments").Range("C2").End(xlDown)))

    ShArrival =
Application.WorksheetFunction.Transpose(Sheets("Shipments").Range("E2",
Sheets("Shipments").Range("E2").End(xlDown)))

    ShDeadline =
Application.WorksheetFunction.Transpose(Sheets("Shipments").Range("F2",
Sheets("Shipments").Range("F2").End(xlDown)))

    vehiclespeeds =
Application.WorksheetFunction.Transpose(Sheets("Vehicles").Range("B2",
Sheets("Vehicles").Range("B2").End(xlDown)))

    i = 1

    Do While i <= NumModes

        populateneededtime i, shsink

        i = i + 1

```

```

Loop
n = 1
k = 1
Do While n <= numshipments
    Do While k < NumModes And found = False
        If SimpleNetwork(k)(shsource(n), shsink(n)) / vehiclespeeds(k) +
shUnloadTime(k, n) <= ShDeadline(n) - ShArrival(n) + 1 Then
            found = True
            FeasArray(n) = k
        End If
        k = k + 1
    Loop
    If found = False Then
        FeasArray(n) = k
    End If
    found = False
    k = 1
    n = n + 1
Loop
End Sub

```

Sub PopulateSimpleNetwork() 'This converts the simple networks generated by Dijkstras algorithm into arrays, for speed.

Dim i As Integer

Dim transfervariable() As Variant

ReDim SimpleNetwork(1 To NumModes)

i = 1

Do While i <= NumModes

With Sheets("Simplified Network " & i).Range("B2")

transfervariable = Range(.Offset(0, 0), .End(xlDown).End(xlToRight))

End With

SimpleNetwork(i) = transfervariable()

i = i + 1

Loop

End Sub

## Bibliography

- Dantzig, G. B., and J. H. Ramser. (1959). "The Truck Dispatching Problem." *Management Science* 6.1: 80-91. Print.
- Lu, Quan, and Maged Dessouky. (2004). "An Exact Algorithm for the Multiple Vehicle Pickup and Delivery Problem." *Transportation Science* 38.4: 503-14. Print.
- Moccia, Luigi, Jean-Francois Cordeau, Gilbert Laporte, Stefan Ropke, and Maria Valentini. *Modeling and Solving a Multimodal Routing Problem With Timetables and Time Windows*. Tech. Dipartimento Di Elettronica, Informatica e Sistemistica, Università Della Calabria, n.d. Web. 20 Nov. 2012. <<http://www.diku.dk/~sropke/>>.
- Psaraftis, H. N. (1983). "An Exact Algorithm for the Single Vehicle Many-to-Many Dial-A-Ride Problem with Time Windows." *Transportation Science* 17.3: 351-57. Print.
- Psaraftis, Harilaos. (1980). "A Dynamic Programming Approach to the Single-Vehicle, Many-to-Many Immediate Request Dial-a-Ride Problem." *Transportation Science* 14: 130-54. Print.
- Savelsbergh, M. W. P., and M. Sol. (1995). "The General Pickup and Delivery Problem." *Transportation Science* 29.1: 17-29. Print.
- Sexton, T. R., and L. D. Bodin. (1985). "Optimizing Single Vehicle Many-to-Many Operations with Desired Delivery Times: I. Scheduling." *Transportation Science* 19.4: 378-435. Print.
- Verma, Sushil, and Maged Dessouky. (1999). "Multistage Hybrid Flowshop Scheduling with Identical Jobs and Uniform Parallel Machines." *Journal of Scheduling* 2.3: 135-50. Print.
- Wagner, Harvey M. (1959). "An Integer Linear-programming Model for Machine Scheduling." *Naval Research Logistics Quarterly* 6.2: 131-40. Print.

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1. REPORT DATE (DD-MM-YYYY) 21-03-2013		2. REPORT TYPE Master's Thesis		3. DATES COVERED (From — To) Sep 2011-Feb 2013	
4. TITLE AND SUBTITLE Vehicle Minimization for the Multimodal Pickup and Delivery Problem with  Time Windows				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S) Clapp, Benjamin A.				5d. PROJECT NUMBER 13S141	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Air Force Institute of Technology Graduate School of Engineering and Management (AFIT) 2950 Hobson Way WPAFB OH 45433-7765				8. PERFORMING ORGANIZATION REPORT NUMBER AFIT-ENS-13-M-03	
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) Amy Pappas, CIV USTRANSCOM/TCAC 508 Scott Drive Scott AFB IL 62225-5357 amy.a.pappas.civ@mail.mil 618-220-7758 / DSN 770-7758				10. SPONSOR/MONITOR'S ACRONYM(S) TCAC	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION / AVAILABILITY STATEMENT APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED					
13. SUPPLEMENTARY NOTES This material is declared a work of the U.S. Government and is not subject to copyright protection in the United States.					
14. ABSTRACT The algorithm proposed here is used for heuristic solutions for the Multimodal Multiple Vehicle Routing Problem with Unloading Capacity, Pickup and Dropoff, and Time Windows, solved so as to minimize the number of vehicles used, subject to varying objective function values for each vehicle. The MVRP is simplified and split into a routing problem and a scheduling problem. The routing problem is addressed by Dijkstra's Algorithm. This generates a new network for the second stage of the algorithm. It is assumed that the shortest path is the correct path to use, and shipments each travel unimodally. The scheduling problem is addressed by treating the various paths as though they were machines, with vehicle number being treated approximately as capacity for the machines, and unloading capacity being treated as a second stage in the processing. The problem is analyzed by assigning all shipments which can be assigned elsewhere away from the most expensive mode and then assigning only leftover shipments to the most expensive mode. Multiple resolutions of the scheduling problem result in feasible solutions for less expensive modes, which results in a feasible solution for every mode, and a low cost solution in terms of vehicles used.					
15. SUBJECT TERMS Transportation Routing Heuristic VRP FSMP					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			Dr. Jeffery Weir ENS
U	U	U	UU	93	19b. TELEPHONE NUMBER (Include Area Code) (937)255-3636, ext 4523